Economics
The Open-Access, Open-Assessment E-Journal

Discussion Paper
No. 2011-16 | June 8, 2011 | http://www.economics-ejournal.org/economics/discussionpapers/2011-16

The U.S. Government's Social Cost of Carbon Estimates after their First Year: Pathways for Improvement

Robert E. Kopp
U.S. Department of Energy, Washington,
and American Association for the Advancement of Science, Washington

Bryan K. Mignone
U.S. Department of Energy, Washington

Abstract In 2010, the U.S. government adopted its first consistent estimates of the social cost of carbon (SCC) for government-wide use in regulatory cost-benefit analysis. Here, we examine a number of the limitations of the estimates identified in the U.S. government report and elsewhere and review recent advances that could pave the way for improvements. We consider in turn socioeconomic scenarios, treatment of physical climate response, damage estimates, ways of incorporating risk aversion, and consistency between SCC estimates and broader climate policy.

Paper submitted to the special issue
The Social Cost of Carbon

JEL Q54, Q58
Keywords Climate change; social cost of carbon

Correspondence Robert E. Kopp, Office of Climate Change Policy and Technology, U.S. Department of Energy, 1000 Independence Ave., SW, Washington, DC 20585, USA, and AAAS Science & Technology Policy Fellow, American Association for the Advancement of Science, Washington, DC 20005, USA; e-mail: rkopp@alumni.caltech.edu.

This paper represents the personal views of the authors. It does not reflect the official views or policies of the United States government or any agency thereof, including the U.S. Department of Energy.

1 Introduction

1.1 Development of the U.S. Social Cost of Carbon Estimates

The social cost of carbon (SCC) is the marginal external cost of a unit emission of CO_2, denominated in terms of forgone consumption and based upon the damages inflicted by that emission upon global society through additional climate change. The value of the SCC is generally estimated in an integrated assessment modeling (IAM) framework that couples a baseline socioeconomic scenario, a climate-carbon cycle model that transforms emissions into temperature, and a function for transforming temperature change (implicitly or explicitly by way of climate change impacts) into economic damages (Figure 1).

In 2010, the United States government established its first consistent estimates of the SCC for government-wide use in cost-benefit analysis of federal regulations (Interagency Working Group on the Social Cost of Carbon, United States Government, 2010). Its analysis relied upon the climate and damage modules of three reduced-form IAMs – DICE 2007 (Nordhaus, 2008), PAGE 2002 (Hope, 2006) and FUND 3.5 (Anthoff and Tol, 2010; Tol, 1997). Five socio-economic scenarios and three fixed discount rates (5%, 3%, and 2.5%) were specified exogenously. Pooling across models and socio-economic scenarios, the report provided four time series of SCC values, increasing over time and starting in 2010 at \$5, \$21, \$35, and \$65 per ton CO_2 (in 2007 dollars). The first three values correspond to mean estimates at discount rates of 5%, 3%, and 2.5%; the last value is the 95th percentile of pooled estimates at the 3% discount rate.

The report describing the analysis, first published in March 2010 as an appendix to the Technical Support Document for DOE's Energy Conservation Standard (ECS) for Small Electric Motors (U.S. Department of Energy, 2010b), identified a number of limitations with the three IAMs it employed to calculate climate change damages. In particular, it noted that all three models:

- Incompletely treated non-catastrophic damages, for instance omitting ocean acidification and other effects on ecosystem services;
- Incompletely treated potential catastrophic damages, such as the effects of major reorganizations of ocean circulation or massive ice sheet melt;
- Crudely extrapolated damages calibrated at low degrees of warming (around 2.5°C) to high degrees of warming (in some scenarios, 10°C or more);
- Failed to incorporate inter-sectoral interactions (such as the effects of water resources on agriculture) and inter-regional interactions (such as the effects of human migration between regions);
- Did not account for the imperfect substitutability of environmental amenities, assuming instead that it is possible to fully replace damaged natural systems with market goods; and
- Incompletely and opaquely treated adaptation to climate changes.

As the report noted, the analysis also did not take into account risk aversion, a factor which plays a large role in broader climate policies, which are often framed as insurance against the risks of climate change. Indeed, by opting for fixed discount rates instead of employing the

Ramsey discounting built into all three models, the analysis eliminated the limited mechanism available in the models for incorporating risk aversion.

Subsequent critiques noted that the socio-economic scenarios employed in the report significantly undersample the range of plausible futures (O'Neill, 2010) and that the strong simplifications employed in the IAMs' climate models can significantly affect final results (Marten, 2011; van Vuuren et al., 2011; Warren et al., 2010).

The report expressed "all due humility" about the limitations of the analysis and pledged that the United States government would periodically review and reconsider SCC estimates.

To lay the groundwork for re-examination of the assumptions used in the SCC analysis, the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) convened a pair of workshops in Nov. 2010 and Jan. 2011. These workshops focused respectively on the broader methodological challenges of calculating climate change damages (http://go.usa.gov/426) and on specific sectoral estimates of climate change impacts and damages that might inform the construction and calibration of damage functions (http://go.usa.gov/42F). Papers from these workshops will be published in a forthcoming special issue of *Climatic Change*. In addition, significant independent advances have occurred in the relevant research since the U.S. government analysis began.

After first examining the application of the U.S. SCC estimates in recent practice, this paper reviews these advances. We start by considering the three principle components of the SCC calculation: socio-economic scenario development, physical climate modeling, and damages estimation. We then examine the challenge of taking risk aversion into account when integrating across possible future states of the world and the consistency between SCC estimates and broader climate policy. We conclude with a discussion of possible steps for refining SCC estimates and directions for future research.

1.2 Initial Applications of the U.S. SCC estimates

Since the release of the U.S. government SCC analysis, its estimates have been employed in several rulemakings by the U.S. Department of Energy (DOE), Environmental Protection Agency (EPA), and Department of Transportation (DOT) (Table 1).

To illustrate how SCC estimates are applied in practice, we consider their use in DOE Energy Conservation Standards (ECS). Although the SCC was employed in two final ECS rules and one proposed rule in 2010, it was only one of many inputs used in determining the rules' stringency. The Environmental Policy and Conservation Act (EPCA) requires that standards be technologically feasible and economically justified, and have positive average lifecycle cost savings, and it prescribes eight criteria for consideration in determining economic justification. As part of their associated economic analyses, ECS rules currently assess consumer net present value (NPV) based on initial costs and energy savings, the global monetized benefits of CO_2, NO_x, and mercury emissions reductions, and the sum of these values.[1]

The monetized benefits of CO_2 are generally a second-order contributor to the NPV of residential and commercial energy efficiency standards, as can be seen by considering the

---

[1] NO_x and mercury reduction benefits are monetized based on literature surveys. Per ton values are around $2 thousand and $17 million per metric ton, respectively, while the total value of NO_x and mercury emission reductions for ECS rule is typically (e.g., U.S. Department of Energy, 2010b) at least an order of magnitude less than CO_2 reduction benefits.

average cost and carbon intensity of electricity in the United States. The average retail price of electricity in 2009 was about 11 cents/kWh, while average CO_2 intensity was about 0.6 kg/kWh (U.S. Energy Information Administration, 2011a, 2011b)**.** At $21/ton CO_2, this translates to a social cost associated with the climate impacts of average US electric generation of about 1.3 cents/kWh conserved. Thus the current central SCC estimates should increase the monetized benefits of energy efficiency rules for electricity-using products by about ten percent. Higher SCC estimates, or the incorporation of additional benefits of reduced fossil fuel use (e.g., Epstein et al., 2011), would have a larger effect.

For each standards analysis, DOE defines several Trial Standard Levels (TSLs) with increasingly stringent energy efficiency requirements, undertakes a technical and economic analysis of each level, then selects a TSL based on its analysis. Typically, five to eight different levels are considered, with the TSL 1 being the least efficient level and the highest TSL being the maximum technologically feasible. (Masur & Posner (2011) note that the decision to consider only particular discrete TSLs, rather than explore a broader parameter space, limits the role of the SCC in stringency setting.) Table 2 compares the selected TSL for final and proposed rules issued after February 2010 to those TSLs yielding peak NPV at 7% and 3% discount rates, excluding and including externalities. Where ranges are shown, they reflect the range in SCC values.

Most notable are the proposed refrigerator rules and the residential water heater rule. For refrigerators, the inclusion of the SCC supports the selection of a more stringent TSL. Without accounting for externalities, the peak NPV for standard refrigerator-freezers occurs at TSL 1; with externalities (specifically, the monetized costs of CO_2, NOx, and mercury emissions), peak NPV occurs at TSLs 1-3, depending on the SCC value used. DOE selected TSL 3, which was also the choice of a consensus agreement between industry and advocates.

By contrast, the water heater rule illustrates a case in which SCC considerations were marginalized by other factors. The final rule was set at TSL 5, consistent with the peak NPV in the absence of externalities at a 7% discount rate. With externalities included and employing the central SCC estimates, peak NPV occurs at TSL 7 when considering consumer benefits at a 7% discount rate and at TSL 8 when considering consumer benefits and externalities at a 3% discount rate. DOE's selection of a less stringent TSL was dominated by distributional concerns, as can be seen from the text of the rule, which also serves to exemplify the reasoning underlying ECS rulemakings (U.S. Department of Energy, 2010a):

> The Secretary has concluded that at TSL 7, the benefits of energy savings, positive consumer NPV (at 3-percent discount rate), generating capacity reductions, and emission reductions would be outweighed by the negative economic impacts on those consumers that would have to make structural changes to accommodate the larger footprint of the heat pump water heaters, the economic burden on a significant fraction of consumers due to the large increases in total installed costs associated with heat pump water heaters, the disproportionate impacts to consumers in multi-family housing and others with comparatively low usage rates, the large capital conversion costs that could result in a large reduction in [Industry Net Present Value, or] INPV for the manufacturers, and the uncertainties associated with the heat pump water heater market….
>
> The Secretary has concluded that at TSL 5, the benefits of energy savings, positive consumer NPV, generating capacity reductions, economic savings for most consumers, and emission reductions (both in physical quantities and the monetized value of those emissions) outweigh the large capital conversion costs that could result in a large reduction in INPV for the manufacturers and the negative impacts on some consumer subgroups. Further, global benefits from carbon dioxide reductions (at a central value of $21.4 per ton for emissions in 2010) would have a present value of $2.7 billion. These benefits from carbon

> dioxide emission reductions, when considered in conjunction with the consumer savings NPV and other factors described above, support DOE's conclusion that TSL 5 is economically justified.

As this discussion illustrates, the SCC estimates are one of many considerations that inform the regulatory process. In some cases, they have supported the selection of more stringent rules, while in other cases, other factors have proven determinative.

2 Socio-Economic Scenarios

2.1 Challenges of long-term projections

The first step in calculating the SCC requires identifying baseline scenarios for key socio-economic parameters, such as GDP and emissions. Reference scenarios for mitigation typically extend no further than 2100. Examples include those in the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (SRES) (Intergovernmental Panel on Climate Change, 2000), the under-development Shared Socio-economic Pathways (SSPs) (Kriegler et al., 2010), and the reference scenarios employed by most of the models that participate in Energy Modeling Forum (EMF) model comparison exercises (Clarke, 2009).

SCC calculations, however, need multi-century baselines. While projections past 2100 are extremely challenging and at best illustrative, they have a significant effect on the NPV of climate change damages. In DICE 2007's base run, for example, about half of the NPV of total damages at a 3% discount rate comes from damages occurring after 2100 and about 15% comes from damages after 2200. At a 2.5% discount rate, about two-thirds of NPV damages come from impacts after 2100 and one-quarter from impacts after 2200.

The U.S. government analysis employed multi-century extensions of reference scenarios from four of the ten process-based IAMs that participated in the EMF-22 exercise (MiniCAM, MESSAGE, MERGE, IMAGE) (Clarke, 2009). The EMF-participating models include more detailed representations of the climate system, the energy system and, in some cases, other physical and economic systems than do reduced-form IAMs. The four reference scenarios were chosen to span the range of reference CO_2 emissions in all ten participating models. (A fifth scenario employed in the U.S. government analysis averaged 550 ppm CO_2e stabilization scenarios from the same four models.)

As noted by O'Neill (2010), however, the EMF-22 reference scenarios significantly undersample plausible future socio-economic scenarios – an illustration of the general principle that ensembles of complex models tend to oversample the peak and undersample the tails of probability distributions (Roe, 2010). For instance, MiniCAM, MESSAGE, MERGE, and IMAGE all employ moderate population growth scenarios, with population in 2100 in the range of 8.5-10.5 billion. By contrast, the U.N. Low, Medium, and High population scenarios reach 6.2, 10.1 and 15.8 billion in 2100, respectively (United Nations Department of Economics and Social Affairs, 2011). The U.S. government analysis extended the four IAM-based population scenarios to 2300 by assuming that population growth rate declined linearly to zero by 2200, yielding a population range of about 8-12 billion by 2300. By contrast, U.N. projections for 2300, based on a range of plausible assumption about fertility rates, vary from 2 to 36 billion (United Nations Department of Economics and Social Affairs, 2004). O'Neill et al. (2010) observe that varying assumptions about population can have sizeable impacts on global CO_2

emissions; the UN range of population projections for 2100 can lead to a ~±50% range in CO_2 emissions in the same year.

O'Neill (2010) raises similar concerns about the range of GDP scenarios used in the U.S. government analysis, which were based on the EMF scenarios through 2100 and extrapolated a linear decline in the GDP/capita growth rate thereafter. He suggested the need for studies to assess the sensitivity of the SCC to the range in scenarios; assuming it proves significant, he recommended a more thorough process for generating the multi-century socio-economic scenarios needed by the SCC calculations. One approach might be to develop a consistent methodology for extending SSPs to 2300. With the discounting methodology used in the U.S. government SCC analysis, higher future GDP values will increase SCC estimates; with Ramsey discounting, in which the utility of a marginal dollar declines with wealth, the direction of the impact is unclear.

Translating GDP into emissions requires technological assumptions. Here, the U.S. government analysis employed carbon intensities from the EMF models through 2100, and then extended a constant CO_2 intensity decline rate thereafter. The reduced-form IAMs employ a similar approach in their native versions. O'Neill notes that the range of emissions in the scenarios employed by the U.S. government analysis is moderately wider than the range in the extended Representative Concentration Profiles that will be used for the IPCC's Fifth Assessment Report.

2.2 Overshoot and panic?

The reference scenarios employed in the U.S. government analysis may not reflect the most likely human responses to climate change. In keeping with the standard definition of a reference scenario, they were calculated for worlds that neither experience climate change impacts nor implement any mitigation policy. Keeping policy (or the lack thereof) constant, these scenarios were then used to calculate the damages to the global economy resulting from climate change – assuming that human civilization chose to suffer and to adapt to climate change, but never to mitigate. In reality, even a highly myopic society would likely undertake some mitigation efforts once the effects of climate change became sufficiently apparent and severe. More plausible alternative reference scenarios – ones reflecting the probable human response in the absence of significant near-term mitigation – might reflect an "overshoot and panic" response (Figure 2).

"Overshoot and panic" scenarios can be characterized by the degree of warming sufficient to trigger a 'panic' reaction, the level of warming at which society will aim once it panics, and the timescale over which it seeks to achieve this level of warming. For a probabilistic SCC calculation, all three of these parameters could be treated as random variables. Alternatively, assuming that society overcomes barriers to efficient behavior once it starts to panic, the latter two could be calculated through a cost-benefit optimization. In addition to being potentially more realistic, these scenarios have another key benefit: assuming that 'panic' onsets at moderate levels of warming (e.g., 2-4°C), they reduce the contribution to the SCC of highly uncertain economic damages triggered by extreme warming.

3 Physical climate and carbon cycle models in IAMs

Carbon cycle and physical climate models translate greenhouse gas emissions associated with a socio-economic scenario into projections of greenhouse gas concentrations, radiative forcing, and temperature.

Carbon cycle models project the accumulation of carbon dioxide in the atmosphere and its removal into sinks such as the terrestrial biosphere, the surface ocean, the deep ocean, and ultimately sediments. Though about 30-70% of atmospheric carbon dioxide is removed on a timescale of less than a century, a significant chunk (about 10-20%) remains for ten or more millennia (Archer et al., 2009). The long-term dynamics of other climate forcers, such as methane, are generally simpler than those of carbon dioxide; the removal of such forcers from the atmosphere can often be reasonably well approximated by an exponential decay.

The accumulation of greenhouse gases and other climate forcers gives rise to a global energy imbalance that is gradually relieved as the planet adjusts to a new equilibrium temperature. The degree of imbalance is measured by radiative forcing, and the level of equilibrium warming associated with a given forcing is summarized by a parameter known as equilibrium climate sensitivity. In the absence of feedback effects, the equilibrium temperature response to a doubling of CO_2 concentrations (a radiative forcing of 3.7 W/m^2) would be about 1.2°C. Fast-feedback climate sensitivity takes into account amplifying feedbacks that respond to forcing on roughly sub-annual to annual timescales, such as changes in atmospheric water vapor, clouds, and snow and sea ice (Randall et al., 2007). The IPCC's Fourth Assessment Report estimated a 67% probability that the fast-feedback climate sensitivity was between 2°C and 4.5°C per CO_2 doubling, with a most likely value of about 3°C (Hegerl et al., 2007). This assessment was used to help calibrate the probability distribution for climate sensitivity used by the U.S. government analysis.

Since the ocean acts as a heat sink, the Earth does not instantaneously adjust to the equilibrium temperature associated with a forcing. The transient climate response – the warming realized after 70 years of a gradual, 1%/year increase in CO_2 concentration (sufficient to cause a doubling of CO_2) – is one way of assessing this delay. An analysis of twentieth-century warming using three different climate models leads to an estimated median value for transient climate response of 2.1°C, with a 90% range of 1.5°C to 2.8°C (Hegerl et al., 2007; Stott et al., 2006).

As reviewed by van Vuuren et al. (2011), DICE, FUND and PAGE all employ highly simplified representations of these natural systems. For temperature calculations, DICE uses a two-box model of the surface and the deep ocean; for carbon cycle calculations, it employs a three-box model of the atmosphere, surface ocean/terrestrial biosphere, and deep ocean. PAGE and FUND use functional representations of the decay of greenhouse gas concentrations in the atmosphere and the transient adjustment of temperature toward equilibrium.

By contrast, more detailed, process-based IAMs employ a range of more sophisticated climate and carbon cycle models. Several rely upon MAGICC, an upwelling-diffusion energy balance model with a six-box carbon cycle (Meinshausen et al., 2011). IGSM employs an Earth System Model of Intermediate Complexity (EMIC) including representations of atmospheric dynamics and chemistry, sea ice, the terrestrial biosphere, and either a two-dimensional or three-dimensional ocean model (Sokolov et al., 2005). At the high-end of IAM climate model complexity, the Integrated Earth System Model (IESM) project is working to couple the GCAM IAM, which traditionally has employed MAGICC, to the NCAR Community Earth System Model, a fully-coupled global climate model (Clarke, 2010).

Compared to DICE and PAGE, the climate and carbon cycle models in FUND exhibit reduced sensitivity of climate to changes in greenhouse gas emissions (Warren et al., 2010). This reduced sensitivity should lower SCC estimates. Both FUND and PAGE respond less quickly to changes in forcing than do the higher-complexity models that contributed to assessments and group modeling exercises such as the IPCC's Fourth Assessment Report and the Coupled Carbon Cycle Model Intercomparison Project (C4MIP). This slow response will postpone climate impacts and consequently also reduce SCC estimates (van Vuuren et al., 2011).

PAGE incorporates strong climate-carbon cycle feedbacks and therefore exhibits greater post-2100 warming than DICE and FUND (Warren et al., 2010). Indeed, these feedbacks are significantly stronger than in higher-complexity models (van Vuuren et al., 2011), and so will increase SCC estimates by PAGE at low discount rates. By contrast, the carbon cycle model in DICE removes CO_2 from the atmosphere more rapidly than in higher-complexity models (van Vuuren et al., 2011), which will lead to lower SCC estimates.

Marten (2011) examines directly the effects of such simplifications on the social cost of carbon. Using a variant of DICE with the DICE climate model replaced by a three-box upwelling diffusion energy balance model calibrated against MAGICC 5.3, he finds SCC estimates at a 3% discount rate that are about 25% higher than those from FUND and 40-50% less than those from DICE and PAGE.

4 Damages

4.1 Damage function formulation and calibration

In reduced-form IAMs, damage functions translate changes in physical climate parameters – at least temperature, and sometimes other parameters such as CO_2 concentrations – into changes in global production or consumption. The US government analysis employed the default damage functions in DICE, FUND, and PAGE.

In DICE and PAGE, damage functions take the form of a modified polynomial; DICE 2007's default damage function, for example, is given by

$$\begin{gathered} D(T)/Y = 1 - 1/(1 + \eta T^{\beta}) \\ \eta = \eta_{\text{non-catastrophic}} + \eta_{\text{catastrophic}} = 0.28\% \qquad (1) \\ \eta_{\text{non-catastrophic}} = 0.10\%,\ \eta_{\text{catastrophic}} = 0.18\%,\ \beta = 2 \end{gathered}$$

where $D(T)/Y$ represents the fractional reduction in production as a function of warming T, $\eta_{\text{non-catastrophic}}$ scales damages due to gradual and more certain impacts, and $\eta_{\text{catastrophic}}$ scales expected damages due to high-impact, uncertain-probability events. Note that, for sufficiently low values of ηT^{β}, $D(T)/Y \approx \eta T^{\beta}$; the default DICE damage function is thus an approximately quadratic function of temperature at low levels of warming.

Total expected damages in DICE 2007 are thus about 1% of GDP at 2°C of warming, 4% of global GDP at 4°C of warming, and 22% of global GDP at 10°C of warming. The DICE damage function is calibrated at about 2.5°C warming based on a literature review covering damage models for the agriculture, coastal regions, forestry, energy consumption, health, and leisure, as well as upon the modelers' estimates of the value of human settlements and ecosystems (Nordhaus, 2007; Nordhaus and Boyer, 2000). Potential catastrophic impacts are calibrated based on an adjusted mid-1990s expert elicitation study (Nordhaus, 1994). (DICE 2010, which is an unpublished beta version, explicitly estimates sea level rise and adds terms to the denominator of equation (1) that are linear and quadratic in sea level rise.)

FUND more explicitly models sectoral impacts, with FUND 3.5 containing damage functions for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, human health, and extreme weather. It does not attempt to include possible high-impact, uncertain-probability consequences of climate change (Anthoff and Tol, 2010). The version used in the U.S. government analysis projected that climate change would initially have positive benefits – primarily due to reduced cold-stress – with benefits decreasing starting at about 2°C of warming; this version projected net damages at >3°C of warming that leveled off at <10% of global GDP by about 8°C of warming.

The mismatch in the sectoral breakdown of damages between DICE and FUND (Figure 3) highlights the need for considerable refinement of sectoral damage estimates. In this context, it is worth noting that calibration of IAM damage functions against sectoral models is an inherently limited approach that would be strengthened by comparison to retrospective analyses of climate change impacts. For example, Lobell et al. (2011), for example, estimate that the effects of temperature change, precipitation change, and CO_2 fertilization from 1980-2008 led to a global average increase in the price of maize, rice, wheat and soybeans of about 6%.

Moreover, the fat-tail uncertainty in climate sensitivity requires damage functions that yield meaningful results at high levels of warming – in some cases, >10°C. Such levels are well outside the calibration range of DICE and FUND, and as a consequence these functions yield questionable results when so extrapolated. The DICE damage function, for instance, indicates losses of about 33% of GDP at 11°C of warming – a large amount, but one that prima facie seems inconsistent with the suggestion from recent climate modeling (Sherwood and Huber, 2010) that such warming would render uninhabitable the current homelands of most humans.

IAM damage functions would benefit from the addition of calibration points at temperature beyond 3°C. In particular, integrative studies bringing together natural and social scientists to examine suites of climate change impacts and plausible associated economic damages in a 4°C or 8°C warmer world would help identify appropriate functional forms. In the absence of such studies, there are few reasons to consider the default damage functions but exclude from consideration the suite of alternative functional forms for DICE-like models that have been proposed in the literature (Ackerman et al., 2010; Azar and Lindgren, 2003; e.g., Lempert et al., 2000; Sterner and Persson, 2008; Weitzman, 2010). Golub et al. (this issue) examine the impact of these alternative formulations on the SCC.

4.2 High-consequence "catastrophic" impacts

As noted by the U.S. government report and due in part to the near absence of the underlying economic literature, the damage functions of IAMs poorly handle high-consequence "catastrophic" climate change impacts. Lenton et al. (2008) identify a suite of possible Earth system "tipping elements"– elements of the Earth system that could undergo radical changes as climatic thresholds are crossed. Among potential tipping element behaviors are: Arctic sea ice loss, Greenland ice sheet melt and West Antarctic ice sheet collapse, slowdown or shutdown of the Atlantic Meridional Overturning Circulation, changes in the amplitude or frequency of El Niño-Southern Oscillation (ENSO), and dieback of the Amazon Rainforest.

Kriegler et al. (2009) conducted an expert elicitation study of the probability of crossing certain tipping points under different climate change scenarios. They find a lower-bound probability of 16% of crossing at least one tipping point in a medium warming scenario (2-4°C above 2000 levels) and a lower bound probability of 56% of crossing at least one tipping point in a high warming scenario (>4°C above 2000 levels).

Estimates of the probability of crossing Earth system tipping points can be informed by the study of the geological record of past warm periods. For example, Earth history can provide information about the susceptibility of ice sheets to melt (e.g., Kopp et al., 2009), potential changes to ENSO (e.g., Fedorov et al., 2006), and carbon cycle feedbacks that might amplify future warming (e.g., Zachos et al., 2008).

The three reduced-form IAMs used in the U.S. government analysis handle possible catastrophic impacts in different ways. The DICE 2007 damage function includes expected damages associated with a potential catastrophe causing a permanent loss of 30% of global GDP, with the probability of that catastrophe set based on adjustments to an expert elicitation study conducted in the early 1990s (Nordhaus, 1994; Nordhaus and Boyer, 2000). PAGE 2002 assumes that a climatic "discontinuity" causing between 5% and 20% loss of GDP becomes increasingly likely as temperatures increase. FUND does not include potential catastrophic impacts (Figure 4).

It is important to note that crossing an Earth system tipping point is not identical to the onset of a catastrophic climate change event. For example, some major changes in the Earth system may take place over periods long enough for society to adapt with fairly limited costs. With a partial and limited exception in the case of sea level rise associated with ice sheet collapse, the literature on the economic consequences of Earth system tipping points is extremely sparse (but see Lenton et al., 2009).

4.3 Inter-sectoral and inter-regional interactions

As the U.S. government report highlighted, another area of weakness in the IAM damage functions involves interactions between sectors and between regions. Warren (2011) notes the potential of process-based IAMs like GCAM (Clarke, 2010) to address such interactions. She notes some intersectoral interactions which have been quantified but not typically included in integrated assessments, including the effects of:

- Changes in biome type on soil moisture content, evapo-transporation rate, and thus overall hydrology;
- Farmland loss owing to sea-level rise and salinization on the agriculture sector;
- Loss of pollinators, loss of wild crop types, and pest and diseases on agriculture;
- Changes in coastal ecosystems on coastal regions and biodiversity;
- Land conversions owing to shifts in agricultural production on terrestrial ecosystems;
- Keystone species extinction on terrestrial ecosystems;
- Lost ecosystem services on human health.

She also identifies a number of poorly quantified impacts, including the effects of:

- Changes in nutrient run-off on coastal regions;
- Agricultural intensification on biodiversity;
- Loss of calcifying species due to ocean acidification on marine ecosystems;
- Construction on dams on human health;
- Saltwater intrusion on human health;
- Subsidence and dam construction on settlements and infrastructure.

Regarding interregional interactions – in particular human migration – Warren suggests that a process-based approach may be infeasible and instead recommends a scenario-based methodology. She notes projections that, in a 4°C warmer world, about 800 million people are expected to experience increased water stress and that 30% of global land area (up from 1% today) is expected to experience drought at any one time.

4.4 Complementary approaches

Cooke (2010) suggests using “outer measures” of climate change damages as a complement to the “inner measures” currently employed. By analogy to mathematical measure theory, an “outer measure” assesses a superset of the true set of damages, while an “inner measure” assesses a subset of damages. (An inner measure of climate damages can be compared to the proverbial man looking for his keys only in the illuminated areas under a streetlight, while an outer measure might encompass the entire area he has traversed since he last saw his keys.) As the outer measure becomes more tightly defined and the inner measure more comprehensive, they should converge. The damage estimates currently employed are all inner measures, built up from estimates of individual sectoral impacts and, as noted previously, often missing potential key effects. Cooke suggests that the quantitative literature on the relationship between climate and development could help guide the construction of outer (or at least alternative and independent) measures. For example, analyzing cross-section municipal data from twelve countries in the Americas and 2 to 5 decades of national-level panel data from 136 countries, Dell et al. (2009) estimate that, net of adaptation, warming acts to decelerate growth by about 0.5%/year per degree C. If GDP grows at 3%/year under the reference scenario, then by Cooke’s reasoning, one outer measure of expected GDP loss after 50 years of 3°C warming would be about 50% of GDP (i.e.. GDP after 50 years would have grown by 110% instead of 340%).

5 Risk aversion

The U.S. government SCC estimates are based on Monte Carlo samples from the probability distribution for climate sensitivity, as well as for a suite of other random variables employed in the standard version of PAGE and the stochastic version of FUND. These Monte Carlo samples yield probability distributions for the social cost of carbon. One key question is how to summarize these distributions in a single value. For three of its four SCC estimates, including the central estimate, the report took the mean of the distribution – the value that would be used by a risk-neutral utility maximizer – while the fourth value was sampled from the 95th percentile of the distribution with a 3% discount rate.

Yet climate policy is generally viewed not simply as a way of maximizing risk-neutral expected utility but as a way of managing risk. The United Nations Framework Convention of Climate Change (UNFCCC), for example, seeks to “prevent dangerous anthropogenic interference with the climate system” (United Nations, 1992). This framing suggests not risk neutrality, but risk aversion, and indicates the need for summary values that give extra weight to low-probability but high-consequence states of the world (e.g., Keller et al., 2005; Oppenheimer and Petsonk, 2005).

Kousky et al. (this issue) review approaches for incorporating risk aversion into the social cost of carbon, which can be viewed as falling into two basic categories: those that operate through discounting and those that do not. We highlight some key points here.

5.1 Risk aversion in Ramsey discounting

The conventional Ramsey (1928) discounting framework, as employed in the standard versions of DICE, FUND, and PAGE, assumes an isoelastic utility function, with the time-discounted marginal utility u of consumption c and time t given by:

$$u(c,t) = c^{-\eta}/(1+\rho)^t \tag{2}$$

where η is the elasticity. Assuming a consumption growth rate of g, such that $c(t) = c_0(1+g)^t$, and a pure rate of time preference of ρ, the deterministic discount rate r can be calculated by equating the utility of one unit of consumption at time t with the utility of $(1 + r)$ units of consumption at time $(t + 1)$. It is given by

$$c_0^{-\eta} = (1+r)\,[c_0\,(1+g)]^{-\eta}/(1+\rho)$$

$$(1+r) = (1+\rho)(1+g)^{\eta}, \tag{3}$$

which can be approximated by the well-known expression

$$r \approx \rho + g\eta. \tag{4}$$

By definition, η is the coefficient of relative risk aversion and a measure of both inter-temporal and intra-temporal inequality aversion. Social welfare is calculated in this framework by summing time-discounted utility across individuals and time periods and averaging across states of the world. If $\eta > 0$, low-consumption states of the world, time periods, and individuals contribute more per unit consumption to social welfare than do their high-consumption counterparts (equation 2). Equivalently, because r is correlated with the consumption growth rate (equation 4), states of the world that experience slow or negative growth are discounted less heavily than high-growth states.

The inclusion of moderate levels of risk aversion can therefore have a large impact on SCC values. For example, Anthoff et al. (2009) find in FUND that incorporating risk aversion increases SCC estimates by about \$20/ton CO_2 (using $\rho = 1.1\%$ and $\eta = 1.5$, parameters that would yield a deterministic discount rate of about 5% per annum).

The U.S. government analysis does not employ Ramsey discounting. Instead, it employed flat discount rates of 2.5%, 3.0% and 5.0% per annum. Effectively, it set η to zero, removing the only form of risk aversion incorporated into the standard versions of the reduced-form IAMs. By comparison, η is frequently set to 1.0, as in the Stern Review (Stern, 2007). DICE 2010 defaults to 1.5, while earlier versions default to 2.0.

Dietz (2010) discusses a general problem with isoelastic utility functions: namely, that marginal utility tends to infinity as consumption tends to zero. As a consequence, as observed by Weitzman (2009), cost-benefit analysis with these utility functions fails in situations with extremely high-impact, low-probability ‘fat tails.’ One approach to dealing with this problem, followed by Weitzman and by Dietz, is to bound consumption by assuming that per capita consumption cannot fall below something analogous to the value of a statistical life. Employing fat-tailed distributions for damage function exponents (a log-normal distribution with a mean of 1.9 and 90% range of 1.1 to 3.1) and climate sensitivity in a DICE-like framework, Dietz finds that, with damages bounded at 99% of consumption, $\rho = 1.5\%$ and $\eta = 3$, the mean SCC is \$346/ton CO_2, with a 90% confidence range of \$5 to \$1359/ton. (Note that, at a growth rate of

2-3%, these parameters would imply a total discount rate of about 7%-11% -- yielding a very small SCC in a deterministic framework.)

5.2 Risk aversion in discounting beyond the Ramsey framework

As noted previously, another key limitation of the Ramsey discounting approach is that it does not distinguish between risk aversion, aversion to inter-temporal inequality, and aversion to intra-temporal inequality. Assuming future generations are wealthier, high risk aversion (which will increase the desire to abate greenhouse gas emissions) will thus also be correlated with a high inter-temporal discount rate (which will reduce the desire to abate emissions). However, results from the Climate Ethics Survey (Atkinson et al., 2009) indicate that attitudes toward risk aversion, inter-generational, and intra-generational equity are only weakly correlated. This survey of over 3000 people found a median value of η in the context of risk aversion in the range of 3-5, a median value of η in the context of intra-temporal equality in the range of 2-3 (but with the modal peak at >7.5 and a secondary peak at <1.0). A median value of η in the context of inter-temporal equality of about 8.8 suggests a strong aversion to downward sloping consumption paths.

Traeger (2009) reviews some relevant approaches for discounting under uncertainty and for separating out the distinct roles of η. As one example, Crost and Traeger (2010) present a recursive dynamic programming model based upon stochastic growth in a simplified version of DICE. They find that treating uncertainty over climate sensitivity and damages in such a framework (with $\eta = 2$ in a risk aversion context and 0.67 in an intertemporal context, based on Vissing-Jørgensen and Attanasio, 2003) increases SCC estimates off an optimal emissions trajectory by about \$15-\$30/ton CO_2 compared to using the discounting parameters in DICE 2007 ($\eta = 2$ in all contexts).

Kaplow et al. (2010) note that the positive parameters used to describe the preferences of individuals, which are descriptive and can be inferred from observed market behavior or from surveys, are not necessarily identical to the normative social preferences appropriate for evaluating policies that impact individuals, including some (such as those belonging to future generations) who are not market actors. The former appear in individuals' utility functions, while the latter appear in the social welfare function. They suggest separating out these two functions of η and ρ in IAMs.

5.3 Non-discounting approaches to account for risk aversion

While one method for incorporating risk aversion is through discounting, an alternative approach is to employ decision criteria other than expected utility maximization. McInerney et al. (in rev.) contrast expected utility maximization with two alternative criteria:

(1) 'limited degree of confidence' (LDC), which maximizes a weighted average of expected utility and a measure of extreme possible outcomes, and
(2) 'safety first,' which maximizes expected utility subject to a constraint on the probability of high-end impacts.

Both these alternative criteria can inform climate policy. The marginals of the associated objective functions can also generate values suitable for consideration as social cost of carbon estimates. For example, as used by McInerney et al., the measure of the worst outcome for the LDC criterion is conditional value at risk, which is the expected value of the worst q-th quantile of the outcome distribution; i.e., the LDC criterion maximizes

$$\beta\mathrm{E}[W] + (1 - \beta)\mathrm{E}[W_q] \tag{5}$$

where $(1 - \beta)$ is the weight on high-end outcomes, $\mathrm{E}[W]$ is the expectation of social welfare, and $\mathrm{E}[W_q]$ is the expectation of the worst q-th quantile of welfare. In the paradigm of robust decision-making (Lempert and Collins, 2007), β should reflect the degree of confidence in the probability distribution for W and thus in expected social welfare. Higher values of β reduce optimality in return for greater resilience to violated assumptions. This objective function can be applied in a straightforward fashion to yield a marginal value akin to the SCC:

$$\beta\mathrm{E}[\mathrm{SCC}] + (1 - \beta)\mathrm{E}[\mathrm{SCC}_q]. \tag{6}$$

A similar marginal can be derived from the Lagrangian associated with the ‘safety first’ criterion.

6 Relationship to broader climate policy

6.1 Consistency in assumptions

A single, expected utility-maximizing decision-maker choosing an economy-wide climate policy would select a target emissions path that minimizes the combined costs of climate change impacts and mitigation over time. In the absence of constraints that prevent such a solution, the marginal abatement costs along the cost-minimizing path will be equal to marginal benefits (the SCC value associated with the target path, i.e., the shadow price of carbon).

The inputs needed by such a decision-maker would resemble those needed for estimation of the SCC. On the normative side, they include a pure rate of time preference, a measure of risk aversion, and a measure of inequality aversion. On the positive side, they include a probability distribution for the stream of economic damages conditional on emissions and, distinct from SCC calculations, a probability distribution for abatement costs conditional on emissions.

Under the Copenhagen Accord, the U.S. set greenhouse gas emission targets of 17% below 2005 by 2020 and 83% below 2005 levels by 2050 (Stern, 2010), while in the Cancun Agreement, the world’s governments called for “urgent action” to limit warming to 2°C above pre-Industrial temperatures (United Nations Framework Convention on Climate Change, 2010). Both of these goals implicitly reflect risk-adjusted cost-benefit optimizations, and taken together they also imply some distributional preferences. If known or inferred, the assumptions underlying these optimizations could be used to calculate SCC values, either off the target path or off a reference path. Conversely, given the assumptions underlying current SCC calculations and assumptions about abatement costs, it is possible to calculate associated optimal emissions trajectories.

If consistent assumptions underlie both the SCC calculations and broader climate policy, employing the SCC assumptions to calculate the optimal emissions path should yield back broader climate targets. However, current U.S. government SCC estimates are risk-neutral, whereas broader climate policy is based on risk aversion (e.g., the UNFCCC goal of avoiding “dangerous anthropogenic interference” with the climate system; United Nations, 1992). Moreover, the implicit damage functions underlying broader climate policy may include potential impacts that are excluded from the the default damage functions in the models underlying current SCC calculations. Employing risk neutrality and the default IAM damage functions in an optimization will therefore yield emissions reductions that fall short of accepted targets for broader climate policy.

6.2 Is the baseline SCC the most suitable cost estimate to be using?

Even if the assumptions underlying SCC estimates are chosen to be consistent with broader climate policy, another key question remains: does the SCC calculated off of a baseline emission path provide an appropriate metric with which to evaluate carbon-reducing regulations?

The U.S. government's SCC estimates are meant to enable the incorporation of the marginal climatic benefits of CO_2 mitigation into cost-benefit analyses. Even assuming perfect characterization of climate change damages, however, the baseline SCC may not provide a comprehensive measure of these marginal benefits.

Suppose most climate change damages will be associated with a major Earth system tipping point, and further suppose that baseline emissions push the Earth system well over this tipping point. The baseline SCC will take into account the effects of gradual climate changes that occur in the post-tipping point world. It will not, however, take into account the damages associated with the tipping point, since the planet crosses the tipping point with or without the emission of a marginal ton. Yet society is willing to pay to avoid those damages, and an additional ton of abatement makes it marginally easier to achieve that goal – a benefit not quantified by the baseline SCC.

Ignoring temporal dynamics, Figure 5a shows an example of such a situation, with about 600 Gt C cumulative abatement being necessary to avoid crossing a major tipping point. Note that the illustrative marginal abatement and benefits (SCC) curves intersect at three points, corresponding to maxima (points A and C) and minima (point B) of total welfare change (Figure 5b). The baseline SCC ($30/ton) is nearly indistinguishable from what it would be if the tipping point did not exist, as is the SCC at local welfare maximum A ($25/ton). But at the global cost maximum, which increases total welfare by $14 trillion over baseline and $5 trillion over local maximum A, the SCC and the marginal abatement cost are $84/ton. The $5 trillion that society is willing to pay to end up at point C instead of point B makes no impact on the baseline SCC, and applying the baseline SCC in cost-benefit analyses would exclude abatement options society is willing to pursue to reach the global optimum. These considerations suggest that the SCC calculated at the global optimum provides a more robust measure of the marginal climate benefits of abatement than does the baseline SCC.

The SCC is informed by an underlying Pigouvian logic, and the above example highlights the limits of the Pigouvian framework discussed by Baumol (1972). Imposing a Pigouvian tax equal to the marginal external cost of an economic activity, calculated for a level of the activity corresponding to a maximum of social welfare, will maintain the activity level at the optimum. If the optimal level of an activity is not known a priori, imposing a tax equal to the marginal external cost at the current level of the activity and then updating as the level adjusts will lead to convergence to an optimal value. But (as illustrated in the example above) strong environmental externalities often give rise to non-convex social welfare functions with multiple local maxima, and there is no guarantee that this trial-and-error process will converge to the global maximum.

Baumol therefore suggests instead circumventing the challenges of optimization by identifying an acceptable level of an externality and imposing a tax sufficient to achieve this level. In the climate change context, his suggestion amounts to setting a temperature, concentration or impact target and then employing a carbon price that achieves this target in a cost-effective manner. Consistent with Baumol's proposal, the government of the United Kingdom shifted in 2009 from evaluating regulations using the social cost of carbon to evaluating regulations using "target-consistent" abatement costs (UK Department of Energy and Climate Change, 2009).

7 Next steps

The U.S. government's social cost of carbon estimates have provided its first consistent framework for incorporating the costs of climate change and the benefits of greenhouse gas abatement into the cost-benefit analysis of federal regulations. They supplanted a family of approaches that varied greatly among rules and agencies and most often neglected the costs of climate change altogether. Nonetheless, as the U.S. government report acknowledges, the current estimates are simply a first attempt. Some improvements can be made in light of additional research that has been published since the U.S. government analysis began; other gaps point to the need for further research.

The baseline socioeconomic scenarios employed could borrow from and build upon the SSPs under development for AR 5, with a consistent framework applied for translating UN population projections to 2300 into long-term economic projections. Baseline scenarios that take likely "panic" policy responses into account could also be considered.

The simple climate models in the reduced-form IAMs employed could be upgraded to emulate the best-available results from more sophisticated climate models.

In the short term, the uncertainty associated with calculating climate damages would be better captured by considering a range of damage functions beyond those included by default in DICE, FUND and PAGE, possibly including bounding "outer measures" as well as the more traditional "inner measures." In the longer term, damage models need to be expanded to include missing sectors and to attempt to capture inter-sectoral and inter-regional interactions. Process-based IAMs may play a key role in this expansion.

Integrated assessment modelers face considerable challenges when attempting to incorporate high-impact "catastrophic" damages or extrapolating damages to high levels of warming. Progress in these areas requires more detailed economic impact studies focused on the consequences of catastrophic climate change. Both detailed and integrative studies of climate change impacts under high-end warming scenarios could provide additional calibration points for IAMs, the damages in which are largely calibrated only for low levels of warming. And without including risk aversion in some fashion, the SCC estimates will necessarily be inconsistent with broader climate policy, which are based on implicit or explicit judgments of risk.

Paradoxically, incorporating some of these changes, including non-convex damage functions, into future estimates could yield SCC values even less consistent with broader climate policy unless other methodological refinements are adopted at the same time. In particular, SCC values calculated off of the baseline path when realistic tipping point impacts are included in the damage function will not account for the benefits associated with avoiding those tipping points. Consistency among climate policy efforts will therefore require further refinements to the methodology – such as calculating the SCC off the optimal path – in order to effectively capture these benefits.

Acknowledgements

The authors participated in the U.S. government's interagency working group on the social cost of carbon on behalf of the U.S. Department of Energy. This paper represents the personal views of the authors. It does not reflect the official views or policies of the United States government or any agency thereof, including the Department of Energy. REK was supported by an appointment to the US Department of Energy under the American Association for the Advancement of Science Fellowship Program administered by Oak Ridge Institute for Science and Education. The authors would like to thank A. Bergman, R. Cooke, R. Duke, E. Kopits, C. Kousky, and A. Marten for comments.

Bibliography

Ackerman, F., E. A. Stanton, and R. Bueno (2010), Fat tails, exponents, extreme uncertainty, *Ecol. Econ.*, 69(8), 1657-1665, doi:10.1016/j.ecolecon.2010.03.013.

Anthoff, D., R. S. J. Tol, and G. W. Yohe (2009), Risk aversion, time preference, and the social cost of carbon, *Environ. Res. Lett.*, 4(2), 024002, doi:10.1088/1748-9326/4/2/024002.

Anthoff, D., and R. S. J. Tol (2010), *The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, version 3.5*. URL http://www.fund-model.org/

Archer, D. et al. (2009), Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, *Annu. Rev. Earth Planet. Sci.*, 37(1), 117-134, doi:10.1146/annurev.earth.031208.100206.

Atkinson, G., S. Dietz, J. Helgeson, C. Hepburn, and H. Sælen (2009), Siblings, Not Triplets, *Economics*, doi:10.5018/economics-ejournal.ja.2009-26.

Azar, C., and K. Lindgren (2003), Catastrophic events and stochastic cost-benefit analysis of climate change, *Climatic Change*, 56(3), 245–255.

Baumol, W. J. (1972), On Taxation and the Control of Externalities, *The American Economic Review*, 62(3), 307-322.

Clarke, L. (2009), Overview of EMF 22 International Scenarios, URL http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/

Clarke, L. (2010), Representation of Climate Impacts in GCAM, in: *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Modeling Climate Change Impacts and Associated Economic Damages*, U.S. Environmental Protection Agency and U.S. Department of Energy. URL http://go.usa.gov/rMO

Cooke, R. M. (2010), Managing climate risks, in: *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Modeling Climate Change Impacts and Associated Economic Damages*, U.S. Environmental Protection Agency and U.S. Department of Energy. URL http://go.usa.gov/rMO

Crost, B., and C. P. Traeger (2010), *Risk and aversion in the integrated assessment of climate change*, CUDARE Working Paper. URL http://www.escholarship.org/uc/item/1562s275

Dell, M., B. F. Jones, and B. A. Olken (2009), Temperature and Income, *Am. Econ. Rev.*, 99(2), 198-204, doi:10.1257/aer.99.2.198.

Dietz, S. (2010), High impact, low probability?, *Climatic Change*, doi:10.1007/s10584-010-9993-4.

Epstein, P. R. et al. (2011), Full cost accounting for the life cycle of coal, *Ann. NY Acad. Sci.*, 1219(1), 73-98, doi:10.1111/j.1749-6632.2010.05890.x.

Fedorov, A. V., P. S. Dekens, M. McCarthy, A. C. Ravelo, P. B. deMenocal, M. Barreiro, R. C. Pacanowski, and S. G. Philander (2006), The Pliocene Paradox, *Science*, 312(5779), 1485 -1489, doi:10.1126/science.1122666.

Hegerl, G. C., F. W. Zwiers, P. Braconnot, N. P. Gillett, Y. Luo, J. A. Marengo Orsini, N. Nicholls, J. E. Penner, and P. A. Stott (2007), Understanding and Attributing Climate Change, in: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., and Miller H.L. (Eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom.

Hope, C. (2006), The marginal impact of CO2 from PAGE2002, *Integrated Assessment*, 6(1), 19-56.

Interagency Working Group on the Social Cost of Carbon, United States Government (2010), Appendix 15a. Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866, in: *Final Rule Technical Support Document (TSD): Energy Efficiency Program for Commercial and Industrial Equipment: Small Electric Motors*, U.S. Department of Energy. URL http://go.usa.gov/3fH

Intergovernmental Panel on Climate Change (2000), *Special Report on Emissions Scenarios*, Nakicenovic N. and Swart R. (Eds.), Cambridge University Press. URL http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

Kaplow, L., E. Moyer, and D. A. Weisbach (2010), The Social Evaluation of Intergenerational Policies and Its Application to Integrated Assessment Models of Climate Change, *BE J. Econ. Anal. Poli.*, 10(2), doi:10.2202/1935-1682.2519.

Keller, K., M. Hall, S.-R. Kim, D. F. Bradford, and M. Oppenheimer (2005), Avoiding Dangerous Anthropogenic Interference with the Climate System, *Climatic Change*, 73(3), 227-238, doi:10.1007/s10584-005-0426-8.

Kopp, R. E., F. J. Simons, J. X. Mitrovica, A. C. Maloof, and M. Oppenheimer (2009), Probabilistic assessment of sea level during the last interglacial stage, *Nature*, 462(7275), 863-867, doi:10.1038/nature08686.

Kriegler, E., J. W. Hall, H. Held, R. Dawson, and H. J. Schellnhuber (2009), Imprecise probability assessment of tipping points in the climate system, *Proc. Natl. Acad. Sci.*, 106(13), 5041 -5046, doi:10.1073/pnas.0809117106.

Kriegler, E., B. O'Neill, S. Hallegatte, T. Kram, R. Lempert, R. Moss, and T. Wilbanks (2010), Socio-economic Scenario Development for Climate Change Analysis. URL http://www.ipcc-wg3.de/meetings/expert-meetings-and-workshops/WoSES

Lempert, R. J., M. E. Schlesinger, S. C. Bankes, and N. G. Andronova (2000), The impacts of climate variability on near-term policy choices and the value of information, *Climatic Change*, 45(1), 129–161.

Lempert, R. J., and M. T. Collins (2007), Managing the risk of uncertain threshold responses, *Risk Anal*, 27(4), 1009-1026, doi:10.1111/j.1539-6924.2007.00940.x.

Lenton, T. M., A. Footitt, and A. Dlugolecki (2009), *Major Tipping Points in the Earth's Climate System and Consequences for the Insurance Sector*, World Wildlife Fund and Allianz SE. URL https://www.allianz.com/static-resources/en/press/media/documents/tipping_points.pdf

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber (2008), Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci.*, 105(6), 1786 -1793, doi:10.1073/pnas.0705414105.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts (2011), Climate Trends and Global Crop Production Since 1980, *Science*, doi:10.1126/science.1204531.

Marten, A. L. (2011), Temperature response modeling in IAMs: The effects of oversimplication on the SCC, *Economics Discussion Papers*, No. 2011-11. URL http://www.economics-ejournal.org/economics/discussionpapers/2011-11

Masur, J. S., and E. A. Posner (2011), Climate Regulation and the Limits of Cost-Benefit Analysis, *Calif. Law Rev.*, in press.

McInerney, D., R. Lempert, and K. Keller (in rev.), What are robust strategies in the face of uncertain climate threshold responses?, *Climatic Change*. URL http://www3.geosc.psu.edu/~kzk10/McInerney_et_al_CC_09.pdf

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley (2011), Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1, *Atmos. Chem. Phys.*, 11(4), 1417-1456.

Nordhaus, W. D. (1994), Expert opinion on climatic change, *Am. Sci.*, 82(1), 45-51.

Nordhaus, W. D. (2007), Accompanying Notes and Documentation on Development of DICE-2007 Model, URL http://nordhaus.econ.yale.edu/Accom_Notes_100507.pdf

Nordhaus, W. D. (2008), *A question of balance*, Yale University Press.

Nordhaus, W. D., and J. Boyer (2000), *Warming the World*, 1st ed., The MIT Press.

O'Neill, B. C., M. Dalton, R. Fuchs, L. Jiang, S. Pachauri, and K. Zigova (2010), Global demographic trends and future carbon emissions, *Proc. Natl. Acad. Sci.*, 107(41), 17521-17526.

O'Neill, B. (2010), Multi-century scenario development and socioeconomic uncertainty, in: *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Modeling Climate Change Impacts and Associated Economic*

Damages, U.S. Environmental Protection Agency and U.S. Department of Energy. URL http://go.usa.gov/rMO

Oppenheimer, M., and A. Petsonk (2005), Article 2 of the UNFCCC, *Climatic Change*, 73(3), 195-226, doi:10.1007/s10584-005-0434-8.

Ramsey, F. P. (1928), A Mathematical Theory of Saving, *Econ. J.*, 38(152), 543-559, doi:10.2307/2224098.

Randall, D. A. et al. (2007), Climate Models and their Evaluation, in: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., and Miller H.L. (Eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom.

Roe, G. (2010), Knowability and no ability in climate projections, in: *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Modeling Climate Change Impacts and Associated Economic Damages*, U.S. Environmental Protection Agency and U.S. Department of Energy. URL http://go.usa.gov/rMO

Sherwood, S. C., and M. Huber (2010), An adaptability limit to climate change due to heat stress, *Proc. Natl. Acad. Sci.*, 107(21), 9552 -9555, doi:10.1073/pnas.0913352107.

Sokolov, A. P. et al. (2005), *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation*, Massachusetts Institute of Technology. URL http://globalchange.mit.edu/pubs/abstract.php?publication_id=696

Stern, N. H. (2007), *The economics of climate change*, Cambridge University Press.

Stern, T. (2010), U.S. Submission Under the Copenhagen Accord, URL http://unfccc.int/files/meetings/cop_15/copenhagen_accord/application/pdf/unitedstatescphaccord_app.1.pdf

Sterner, T., and U. M. Persson (2008), An Even Sterner Review, *REEP*, 2(1), 61 -76, doi:10.1093/reep/rem024.

Stott, P. A., J. F. B. Mitchell, M. R. Allen, T. L. Delworth, J. M. Gregory, G. A. Meehl, and B. D. Santer (2006), Observational Constraints on Past Attributable Warming and Predictions of Future Global Warming, *J. Climate*, 19(13), 3055-3069, doi:10.1175/JCLI3802.1.

Tol, R. S. J. (1997), On the optimal control of carbon dioxide emissions, *Environ. Model. Assess.*, 2(3), 151–163.

Traeger, C. P. (2009), Recent Developments in the Intertemporal Modeling of Uncertainty, *Annu. Rev. Resour. Econ.*, 1(1), 261-286, doi:10.1146/annurev.resource.050708.144242.

U.S. Department of Energy (2010a), Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters; Final Rule, *Federal Register*, 75(73), 20112-20236.

U.S. Department of Energy (2010b), Energy Conservation Program: Energy Conservation Standards for Small Electric Motors; Final Rule, *Federal Register*, 75(45), 10874-10948.

U.S. Energy Information Administration (2011a), *Electric Power Annual 2009*. URL http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

U.S. Energy Information Administration (2011b), *Emissions of Greenhouse Gases in the United States 2009*. URL http://www.eia.gov/environment/emissions/ghg_report/

UK Department of Energy and Climate Change (2009), *Carbon Valuation in UK Policy Appraisal: A Revised Approach*. URL http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/carbon%20valuation/1_20090715105804_e_@@_carbonvaluationinukpolicyappraisal.pdf

United Nations (1992), *United Nations Framework Convention on Climate Change*. URL http://unfccc.int/essential_background/convention/background/items/2853.php

United Nations Department of Economics and Social Affairs (2004), *World Population in 2300.* URL http://www.un.org/esa/population/publications/longrange2/2004worldpop2300reportfinalc.pdf

United Nations Department of Economics and Social Affairs (2011), *World Population Prospects: The 2010 Revision*.

United Nations Framework Convention on Climate Change (2010), *The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention*. URL http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf

Vissing-Jørgensen, A., and O. P. Attanasio (2003), Stock-Market Participation, Intertemporal Substitution, and Risk-Aversion, *The American Economic Review*, 93(2), 383-391.

van Vuuren, D. P., J. Lowe, E. Stehfest, L. Gohar, A. F. Hof, C. Hope, R. Warren, M. Meinshausen, and G. K. Plattner (2011), How well do integrated assessment models simulate climate change?, *Climatic Change*, 104(2), 255–285.

Warren, R., M. D. Mastrandrea, C. Hope, and A. F. Hof (2010), Variation in the climatic response to SRES emissions scenarios in integrated assessment models, *Climatic Change*, 102(3-4), 671-785, doi:10.1007/s10584-009-9769-x.

Warren, R. (2011), The role of interactions in a world implementing adaptation and mitigation solutions to climate change, *Phil. Trans. Roy. Soc. A*, 369(1934), 217 -241, doi:10.1098/rsta.2010.0271.

Warren, R., C. Hope, M. Mastrandrea, R. S. J. Tol, N. Adger, and I. Lorenzoni (2006), *Spotlighting the impacts functions in integrated assessments*.

Weitzman, M. L. (2009), On modeling and interpreting the economics of catastrophic climate change, *Rev. Econ. Stat.*, 91(1), 1–19.

Weitzman, M. L. (2010), What is the “damages function” for global warming -- and what difference might it make?, *Clim. Change. Econ.*, 01(01), 57, doi:10.1142/S2010007810000042.

Zachos, J. C., G. R. Dickens, and R. E. Zeebe (2008), An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics, *Nature*, 451(7176), 279-283, doi:10.1038/nature06588.

Table 1: Some Applications of the Interagency SCC estimates, March 2010-February 2011

Date	Agency	Rule	Status	URL
March 2010	DOE	ECS for Small Electric Motors	Final Rule	http://go.usa.gov/r80
April 2010	DOE	ECS for Residential Water Heaters	Final Rule	http://go.usa.gov/r8I
May 2010	EPA/ DOT	Light Duty Vehicles GHG Emissions and CAFE Standards	Final Rule	http://go.usa.gov/r8Q
May 2010	DOT	Automatic Dependent Surveillance—Broadcast (ADS–B) Out Performance Requirements To Support Air Traffic Control Service	Final Rule	http://go.usa.gov/TwD
August 2010	EPA	Federal Implementation Plans To Reduce Interstate Transport of Fine Particulate Matter and Ozone	Proposed Rule	http://go.usa.gov/rMO
Sept. 2010	DOE	ECS for Refrigerators	Proposed Rule	http://go.usa.gov/r8N
Nov. 2010	EPA/ DOT	Heavy Duty Vehicles GHG Emissions and CAFE Standards	Proposed Rule	http://go.usa.gov/r8Q

Table 2: The influence of the SCC on Trial Standard Level selection for Energy Conservation Standards

Product	**Final/ Proposed TSL**	**Highest TSL**	**TSL with peak NPV, w/o externalities**		**TSL with peak NPV, w/ externalities**	
			7%	3%	7%	3%
Polyphase Small Electric Motors (SEMs)	4b	7	4b	4b	4b	4b
Capacitor-start SEMs	7	8	7	7	7	7
Water heaters	5	8	5	7	5-8	7-8
Direct heating equipment	2	6	3	3	3	3
Pool heaters	2	6	2	2	2	2
Standard-size refrigerator-freezers	3 (proposed)	5	1	1	1-3	1-3
Standard-size freezers	2 (proposed)	5	1	3	2-3	3
Compact refrigerators	2 (proposed)	5	1	1	1-3	1

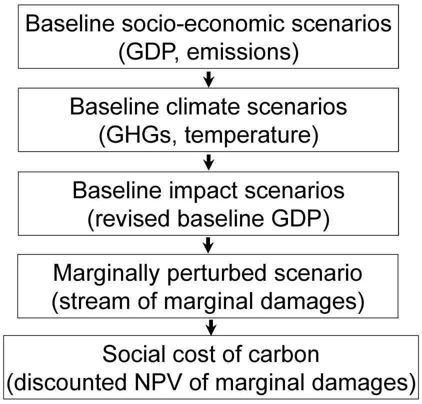

Figure 1: Flow process used in calculating social cost of carbon estimates. A reference socio-economic scenario is used to calculate a reference climate scenario. Economic damages calculated based on this climate scenario are then used to revise the baseline. Next, the baseline scenario is marginally perturbed by the additional or removal of a marginal unit of CO_2 emissions. The value of the stream of damages thus generated is then discounted back to the year of emission.

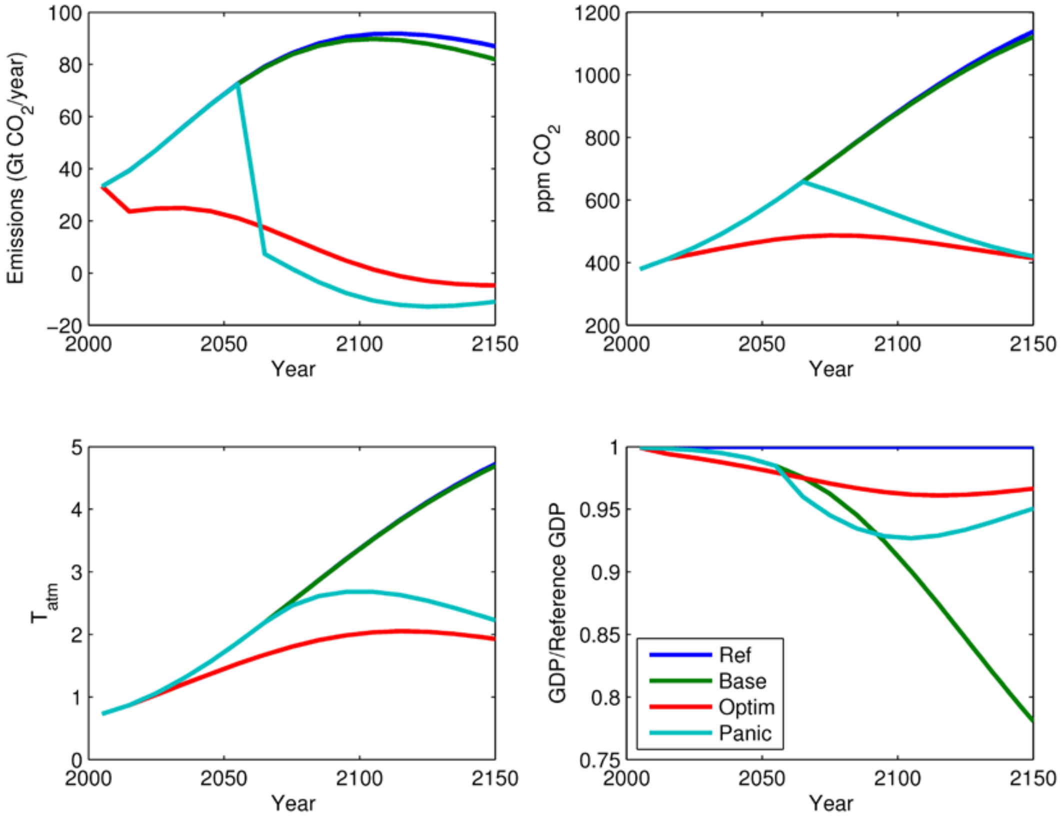

Figure 2: (a) CO_2 emissions, (b) CO_2 concentrations, (c) surface temperatures and (d) GDP (net of climate damages and abatement expenditures) as a fraction of reference scenario GDP for four illustrative scenarios computed using a DICE-like model. “Ref” (blue) was computed in the absence of climate damages; “Base” (green) includes damages but retains the absence of mitigation policy in the Ref scenario; “Optim” (red) is the result of a cost-benefit optimization starting in 2015, while “Panic” follows Base until warming exceeds 2°C and then follows a cost-benefit optimized pathway.

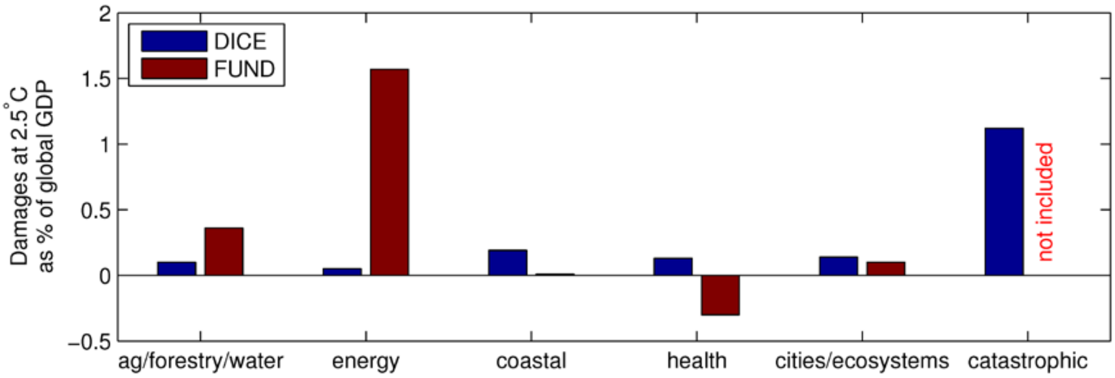

Figure 3: Damages by sector in DICE (Nordhaus, 2007) (blue) and a typical FUND2.9 scenario (Warren et al., 2006) (red) at 2.5°C warming, aggregated into similar sectoral categories. "Ag/forestry/water" bars correspond to the agriculture sector in DICE and the agriculture, forestry and water resources in FUND. "Energy" bars correspond to DICE's "other vulnerable market" sectors and FUND's energy consumption sector. "Coastal" bars correspond to DICE's coastal impacts sector and FUND's sea level rise damages. "Health" bars correspond to human health impacts in both models. "Cities/ecosystems" bars correspond to DICE's damages to settlements and ecosystems and FUND's damages to ecosystems. Catastrophic damages are not included in FUND and are expected values in DICE.

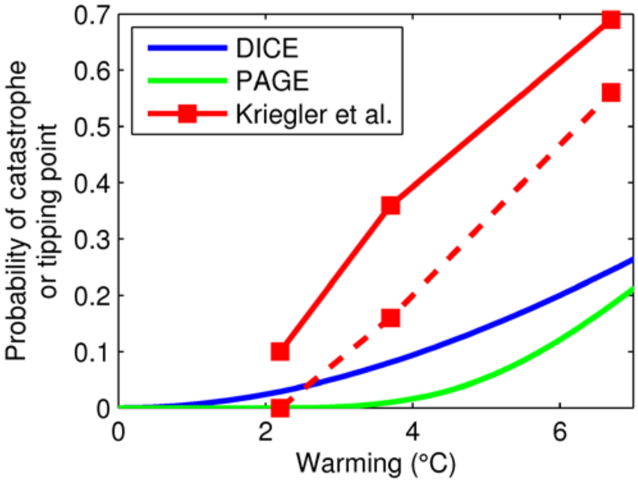

Figure 4: Probability of catastrophic damages in DICE 2007 (blue) and PAGE 2002 (green), compared to lower bounds on the probability of crossing at least one Earth system tipping point according to the expert elicitation study of Kriegler et al. (2009) (red).The DICE curve is inferred based on the relative proportions of catastrophic and non-catastrophic damages at 2.5°C and a definition of "catastrophe" as causing a loss of 30% GDP (Nordhaus, 2007; Nordhaus and Boyer, 2000). In PAGE 2002, catastrophic damages cause loss of 5-20% of GDP. The two curves from Kriegler et al. are based on two different ways of pooling expert responses. Note that a biogeophysical tipping point is not identical to an economic catastrophe, although the examples given by Nordhaus and Boyer (2000) are all associated with tipping points.

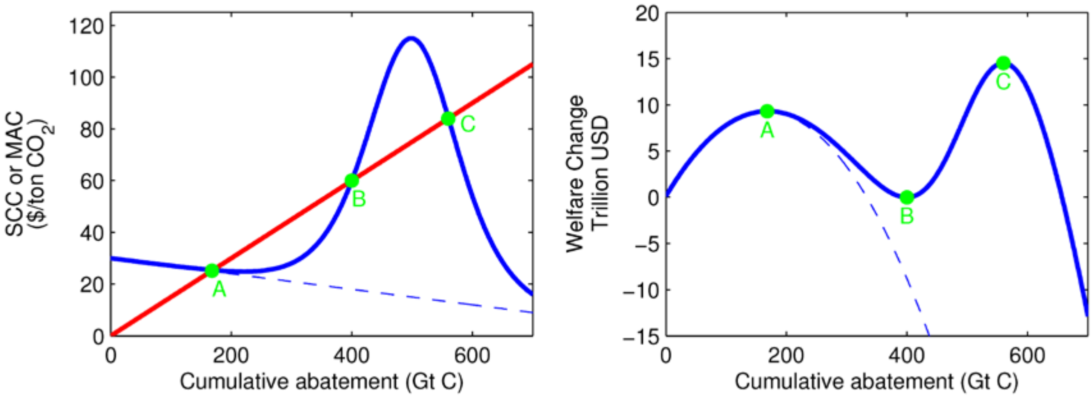

Figure 5: (a) Illustrative marginal abatement costs (red) and benefits (blue) curves and (b) total welfare change for a world in which the majority of climate change damages are associated with a major Earth system tipping point. The dashed lines show corresponding marginal benefits and total welfare change for a world without the tipping point. The marginal abatement cost and benefit curves intersect at three points; point A is a local welfare maximum, point B is a local welfare minimum, and point C is the global welfare maximum. In the absence of the tipping point, point A would be the global maximum and the only intersection point. Baseline emissions carry the world well over the tipping point, but the damages associated with the tipping point have a negligible effect on the SCC at baseline emissions and at local welfare maximum A.